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COORDINATION OF THE VOLUNTARY MOVEMENTS OF MAN IN A ZERO GRAVITATIONAL FIELD (UNDER WEIGHTLESSNESS)

by L. V. Chkhaidze

From "Koordinatsiya Proizvol 'nykh Dvizheniy Cheloveka v Usloviyakh Kosmicheskogo Poleta"
"Nauka" Press, Moscow, 1966

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ABSTRACT

The coordination of the voluntary movements of man in a zero gravitational field (weightlessness) is analyzed on the basis of observational data accumulated under conditions of temporary weightlessness and in flights of artificial manned satellites. The general biomechanical rules of movements performed under weightlessness conditions (e.g., flection and extension of an unburdened or laden arm) are derived from tests carried out according to N. A. Bernshteyn's cyclographic method. The discussions regarding coordination during weightlessness are supplemented by the personal reports of the Soviet cosmonauts G. Titov, A. G. Nikolayev, P. R. Popovich, B. B. Yegorov, A. Leonov, V. Komarov and V. Bykovskiy, as well as the American astronaut John Glenn. It is concluded that even prolonged weightlessness causes no serious or lasting disorders in an individual's movement coordination if he has been properly and adequately trained. However, certain changes should be expected in the dimensionality of the dynamic components of the coordination structure of skills performed in an altered gravitational field, and the limits to the decrease of the elements of the movement structure can reach 50%.

Translator's Note: The first edition of this book titled "Coordination of Man's Voluntary Motions under Conditions of Weightlessness" has been translated and is available as NASA TT F-355.

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COORDINATION OF THE VOLUNTARY MOVEMENTS OF MAN IN A ZERO GRAVITATIONAL FIELD (UNDER WEIGHTLESSNESS)

As pointed out in the introduction to the present work, the conclusions derived in studying the coordination of the individual's voluntary movements in an increased field were extrapolated to the zero field. This made it possible to prognose the possibility of maintaining movement coordination during the most prolonged phase of the astronaut's proposed flight - weightlessness. In this extrapolation, our starting point was that weightlessness is, in essence, a particular case of the gravitational field state.[1] We postulated that the central organs controlling the individual's movements, which are necessarily the first to react to field change, may readjust their activity independently of the direction in which the field changed (if, of course, we exclude the difficulties directly connected with moving the extremities in an increased field where they have taken on weight). In other words, one must assume that, if the mechanisms regulating coordination of the individual's voluntary movements do not stand idly by when his coordination is impaired in increased fields, then under conditions of weightlessness, where the activity of the muscle periphery will in any case be no more complex than when the individual is subjected to G-loads, a similar phenomenon should be expected. /93*

This has been corroborated under conditions of temporary weightlessness and in flights of artificial manned earth satellites. This chapter gives a brief resumé of the data on observations accumulated under these conditions.

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* Numbers in the margin indicate pagination in the foreign text.

[1] Similar approaches to this problem were made by Giovani and Randel (1964), for example, who studied the physiological and psychological aspects of the effect of weightlessness on an individual's organism as a particular case of gravitation.

COORDINATION OF THE VOLUNTARY MOVEMENTS OF MAN UNDER CONDITIONS OF TEMPORARY WEIGHTLESSNESS

Temporary weightlessness lasting up to 40-50 sec may be produced in aircraft flights on a Kepler curve. Many observations /94 of an individual's voluntary movement coordination have been made under these conditions. Let us describe a number of them, which, in our opinion, are of the greatest importance.

As pointed out in our work (Chkhaidze, 1962c), M.A. Cherepakhin completely reproduced, in terms of weightlessness, our method of studying disturbances in the individual's voluntary motor coordination during a gravitational field change.

TABLE 7

Change in Coefficient F in Weightlessness

	Horizontal Flight	Period of Stay in Weightlessness, sec.					
		1-3	4-6	7-9	9-12	13-15	16-18
Mean Value of coefficient of pressure force differentiation	0.56	0.24	0.26	0.29	0.34	0.42	0.52

In Figure 21 we have shown a sample recording of differentiated finger pressure on a solid support made by one of Cherepakhin's testees when passing into weightlessness, while in that state, and during the return to the effect of normal gravitational forces. As is readily ascertained from the figure, the greatest deterioration in the leading dynamic component of this skill may be seen in the first case, i.e., in the transition into weightlessness. By the end of his stay in the zero field (despite its brevity), the testee has to a certain degree regenerated his ability to differentiate pressures (the peaks, indicating the amount of pressure, have the requisite dimensionality). The subsequent transition to the normal field again impairs the coordination of this movement, but it is again soon restored.

Although the above could now corroborate the validity of our extrapolations, let us turn to Table 7, which lists in 3-second time intervals the dynamics of the coefficient F (which we have adopted as the index of pressure force differentiation) under conditions of brief weightlessness. These dynamics are derived from the mentioned recordings by Cherepakhin.

As Table 7 shows, the individual's ability to differentiate the finger pressures under discussion undergoes certain changes. At the first instants of weightlessness, the coefficient F characterizing this ability is very low (which was, however, to be expected). Then follows a slow but steady restoration which, however, does not reach the norms (to all appearances, because the stay in weightlessness is too short).

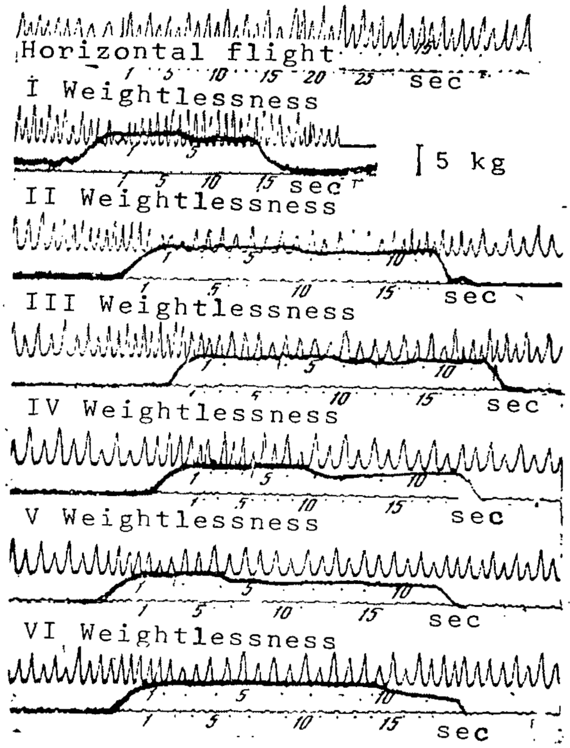

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Fig. 21. Record of Differentiated Finger Pressure Against a Solid Support Performed in a Horizontal Flight (upper curve) and under conditions of complete weightlessness (using the method and conditions of Figure 14). The upward movement of the heavy line corresponds to a lack of gravity. Experiments by M.A. Cherepakhin.

One fact must be pointed out here. If the quoted value of F is graphically expressed, with the duration of skill performance plotted on the abscissa axis in a logarithmic scale (Fig. 22), no direct relation is established between the logarithm of the time required to perform the movement and the value of coefficient F. This coefficient is restored more rapidly than could be expected if compared to the course of this phenomenon in an increased field. The explanation for this may be provided by the easier conditions under which the skill is exercised. As is readily seen, this confirms the truth of the basic premise of the extrapolation mentioned above, and makes it possible to draw the conclusion that under conditions of weightlessness the individual's movement coordination should rapidly regenerate. /96

Fig. 22. Relation between differentiation index of finger pressure force (F) on solid support and logarithm of period of stay in zero gravitational field (my analysis of experiments by M.A. Cherepakhin).

As for the establishment of the corresponding mathematical relationships, we should assume that there is some rule other than a logarithmic one which holds here. Our preliminary analysis of the curves in Figure 21 showed that it is ruled to a certain extent by the following function:

$$\Delta F = Kx^n + C,$$

where ΔF is the improvement in movement coordination, x is the duration of the stay in weightlessness, C is the minimum ability to differentiate forces, K is the coefficient expressing the degree to which the testee was trained, and n is the exponent of the function, which cannot be established precisely at the present, because of the lack of experimental data, but which can be assumed to be close to 2.

Since this dependence is obviously close to a parabolic one, we can expect that it should not take a long time for those sufficiently trained for the effect of weightlessness to restore their /97
movement coordination. This has been confirmed in studies of the biomechanics of an individual's movements which we carried out especially for the purpose of detecting a change in the internal picture of the coordination structure of an individual's movements during temporary weightlessness.

Particular Characteristics of an Individual's Elementary Movements under Weightlessness Conditions

The purpose of this study (which we carried out in 1965 together with I.A. Kolosov, I.F. Chekird, A.V. Yeremin, V.I. Lebedev, V.I. Stepantsov and A.D. Burchuladze) was to investigate the biomechanical laws of movements which are performed in weightlessness in correspondence with the concepts presented in Chapter One, that for a complete analysis of voluntary movements it was necessary to reduce the minimum to the second derivatives, i.e., the accelerations of the gravity centers of the moving joints, and then to calculate the corresponding forces according to Newton's second law of mechanics.

The study covered mainly the biomechanics of an individual's movements in weightlessness, although we also conducted some experiments at low G-forces (1.8-2.2 g) as control observations, in order to compare the data obtained.

The experiments were conducted according to the classic cyclographic method worked out by N.A. Bernshteyn (Popova and Mogilyanskaya, 1934)[2], which is now widely used in the Soviet Union for such observations.

In a general outline, this method involves an ordered fixation of the positions of distal and proximal terminals of the body of an individual executing the movement under investigation relative to a selected system of coordinates. We took profile photographs of a moving arm with three electric bulbs attached to it (the first bulb was fixed in the region of the principal phalanx of the right-hand index finger, the second was attached on the transverse axis of the radiocarpal joint, and the third was on the same axis of the ulnar joint).

A special obturator with four slits, rotated uniformly by an electric motor, was attached in front of the camera. The rate at which the obturator was rotated was such that the time intervals for fixation of sections of the arm were 64 per second. As a result, discontinuous (dotted, in the form of points) trajectories for the movement of the given section of the individual's arm were obtained on the negative.

Figure 23 shows a sample of these trajectories during the execution of one of the movements we investigated.

For the sake of convenience in determining specific coordinates of the points on the trajectories, we imprinted a scale grid on the photographic record. This permitted us to determine the real coordinates of the points with accuracy up to one millimeter. If we consider that the difference in value of the coordinates of neighboring points, attributed to the time (first derivative), is a component of the rate at which a given section of the arm moves along the abscissa or the ordinate, while the difference in value of the first variances, again attributed to the time (second derivative), is its acceleration, then it is sufficient to introduce into this equation the mass of the body section in question

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[2] See the list of references for Chapter I. (Information not included in this translation. See NASA TT F-355 for the appropriate citations.)

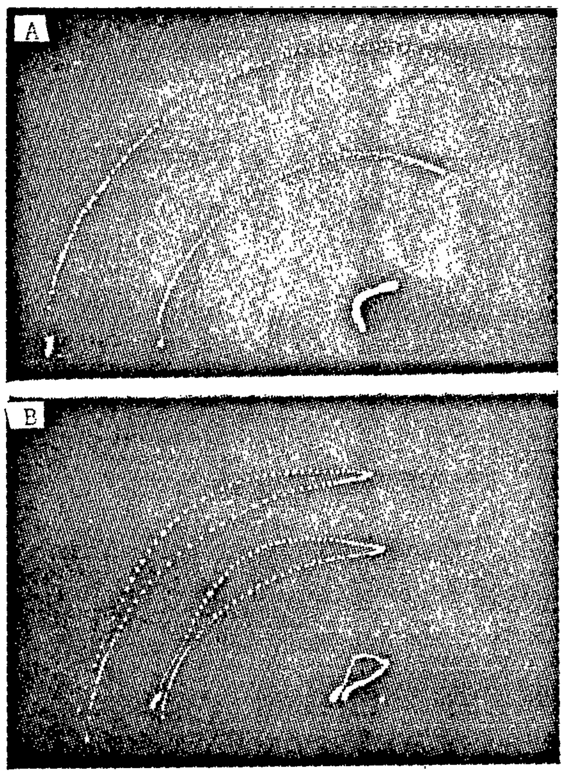

Fig. 23. Movement of sections of an individual's arm during execution of slow flection and extension by an unburdened arm in the ulnar joint, in normal gravitational field (A) and in weightlessness (B).

Taken through the aperture of the rotating oburator at a rate of 64 photographs per sec. In each figure, from left to right, are the trajectories of the small bulbs placed on a projection of the center of gravity of the hand (first phalanx of the index finger) and on the horizontal axes of the radiocarpal and ulnar joints.

in order to determine the force applied to this section at a given moment of time. In determining the vertical component of the forces, the weight of this section is added to the inertial force (obtained from the above calculations). In our studies, it was deducted in all the cases of weightlessness but added in increasing magnitude for a corresponding acceleration stress. /99

We analyzed the data obtained directly according to parametric graphs of the cumulative forces or, less frequently, by constructing the summary vectors of the forces applied to the centers of mass of sections of the arm in certain (the most essential) positions assumed during the execution of the analyzed movement.

The latter was carried out because all the smallest breaks (the so-called "waves") were overlooked on the parametric graphs. Nevertheless, they are always present in some form for a specified movement, while they have different origins.

N.A. Bernshteyn (see Chap. I) established three categories of these waves:

(a) Spontaneous-innervation waves directly reflecting specific nerve impulses and causing the formation of those components of the movement coordination structure which one of the testees (Chkhaidze, 1958) called the principal or leading ones;

(b) Reactive waves of a peripheral origin appearing on these graphs as a reactive reflection of the movements of sections of the body, and causing the appearance of movements of the forces in the coordination structure, which we called concomitant ones;

(c) Waves of a mixed origin, where the reactive-innervation ones occupy the middle position. They reflect the central reaction to reactive forces developing along the periphery. According to L.V. Chkhaidze, the component coordination structures due to these waves are called auxiliary ones.

Thus, having compared the origin, nature, involution and other characteristics of these waves during the execution of some motion, we can describe its entire biomechanical structure or its variability in relative detail, depending on the assigned tasks.

The investigations were carried out by means of a comparative analysis of the nature and origin of these waves during the execution of the following elementary movements of an individual under conditions of weightlessness (20 seconds) and at positive G-loads of 1.8-2.2 g (10-12 seconds) produced in an aircraft flight on a Kepler curve:

(1) Slow flection and extension (in the ulnar joint) of an unburdened arm, which actions were carried out in 2.0 sec; /100

(2) Same movements of a laden arm (the individual grasped in his hand a dumbbell weighing 3.0 kg);

(3) Flection and extension of an unburdened arm, which actions were carried out in a jerking motion in 0.5 sec;

(4) Aimed extension (a finger striking against a designated target) in 0.3 sec.

The ulnar joint of the subjects was not fixed during the execution of these movements. This was done in order that they might experience weightlessness more freely. Although such experimental conditions could somewhat distort the external picture of the skill, they nevertheless did not affect out conclusions, since we attempted to be as close as possible to that state of an individual's stay in a zero gravitation field as what he would find in free flight.

Four men aged 25-35 took part in these experiments. The total number of photographic records analyzed was 25.

General Biomechanical Rules of the Movements Investigated

Despite its apparent simplicity, the coordination structure of the movements we investigated was rather unique, even during a performance under conditions of the normal effect of the Earth's gravity. Moreover, this structure conforms to certain laws.

In the lower half of Figures 24, 25, 26 and 27, we have shown both the parametric graphs for changes in the cumulative forces and the summary vectors of forces applied to the centers of gravity of the wrist for certain positions of the arm.

For the execution of a slow flection of an unburdened or laden arm (Figures 24 and 25), the curves of the component forces form characteristic breaks at the beginning of the movement[3] (nγ for the longitudinal and A for the vertical components). As a result of the combination of these forces, the summary vectors applied to the centers of gravity of the sections of the arm acquire the direction necessary for imparting to the hand the beginning of the corresponding movement (Figures 24 and 25, Positions I and II). It is very natural that the size of these vectors is somewhat larger for the execution of burdened flection than for unburdened flection. Since this part of the movement depends wholly on its meaningful purpose, both of the indicated peaks should relate to spontaneous-innervation waves. Subsequently, several new breaks appear in the curves. They are designated as nA along the vertical components and ζ along the longitudinal ones. These reactive waves are due to the mechanical reaction of the periphery at the beginning of the movement.

[3] According to the tradition introduced by N.A. Bernshteyn, they are usually designated by Greek or Latin letters.

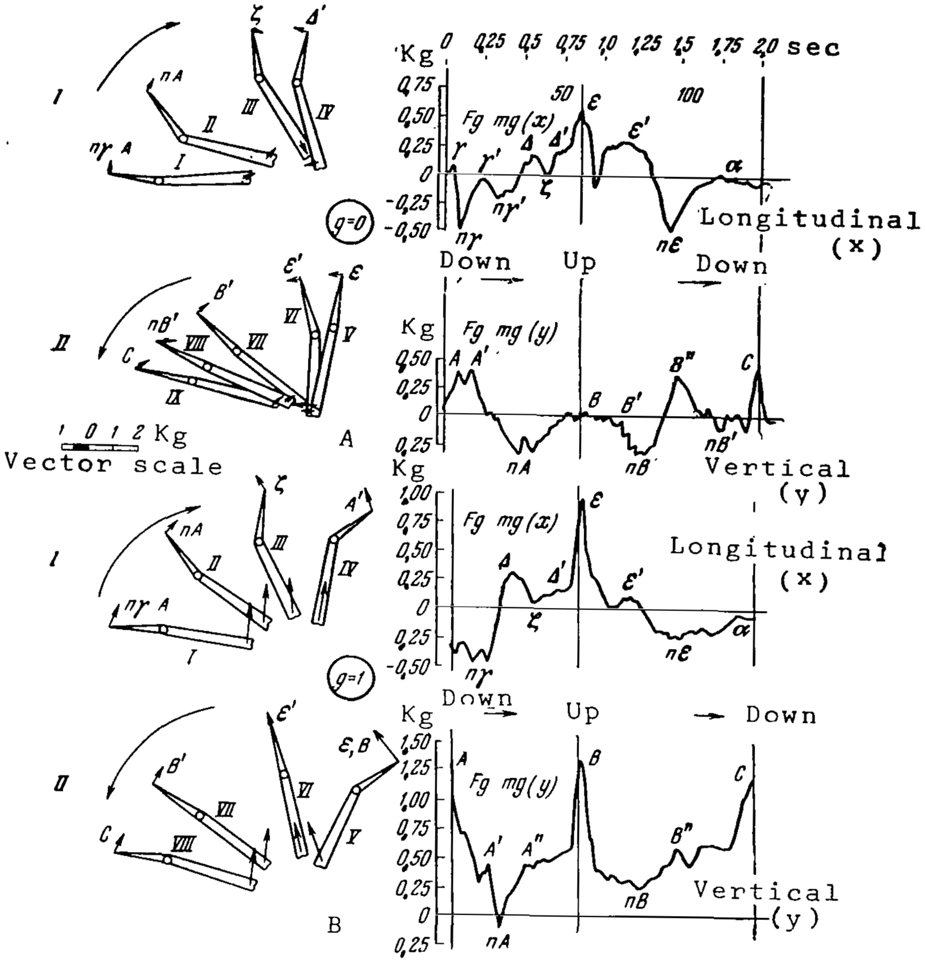

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Fig. 24. Parametric curves of the components of forces (Fg) applied to the center of gravity of the hand, mg (on the right) and actual forces (shown by the vectors, on the left) during the most important phases in the execution of slow flection (I) and extension (II) by an individual's unburdened arm, in the ulnar joint, in weightlessness (A) and in the Earth's normal gravitational field (B). See text for the designations of phases. Orig.

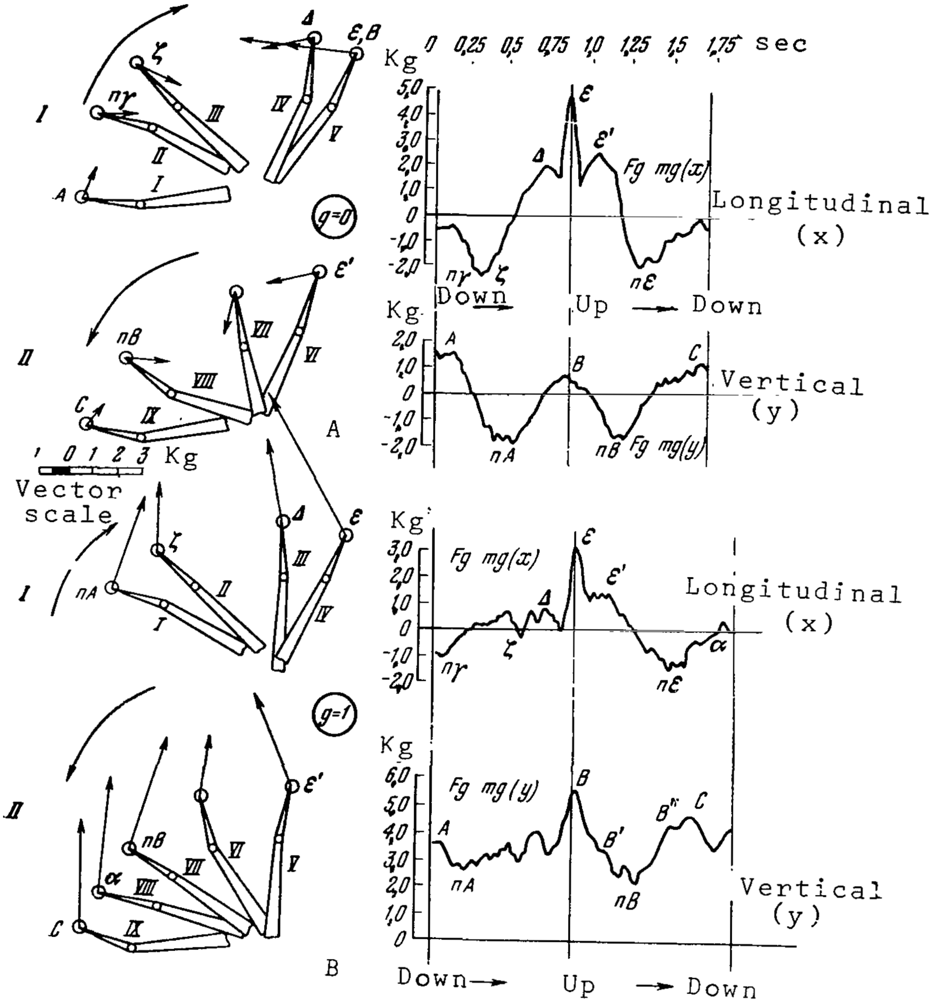

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Fig. 25. Parametric curves of force components for a burdened arm. Orig.

Designations the same as in Figure 24.

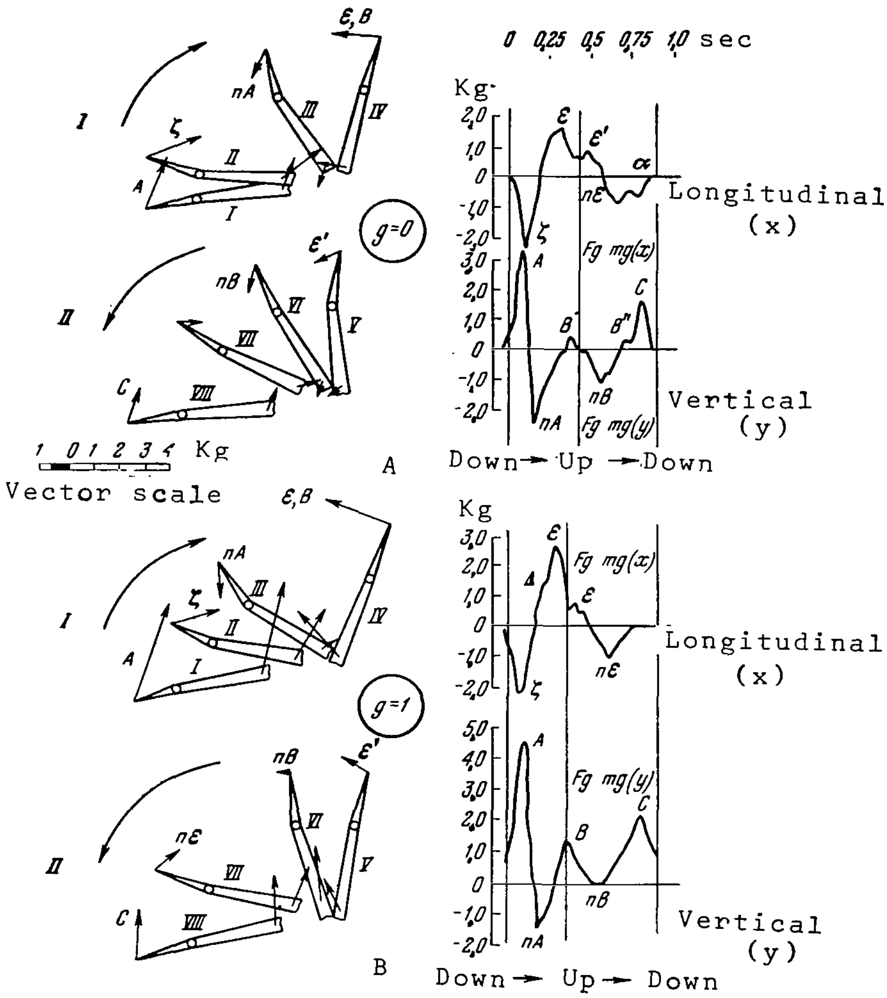

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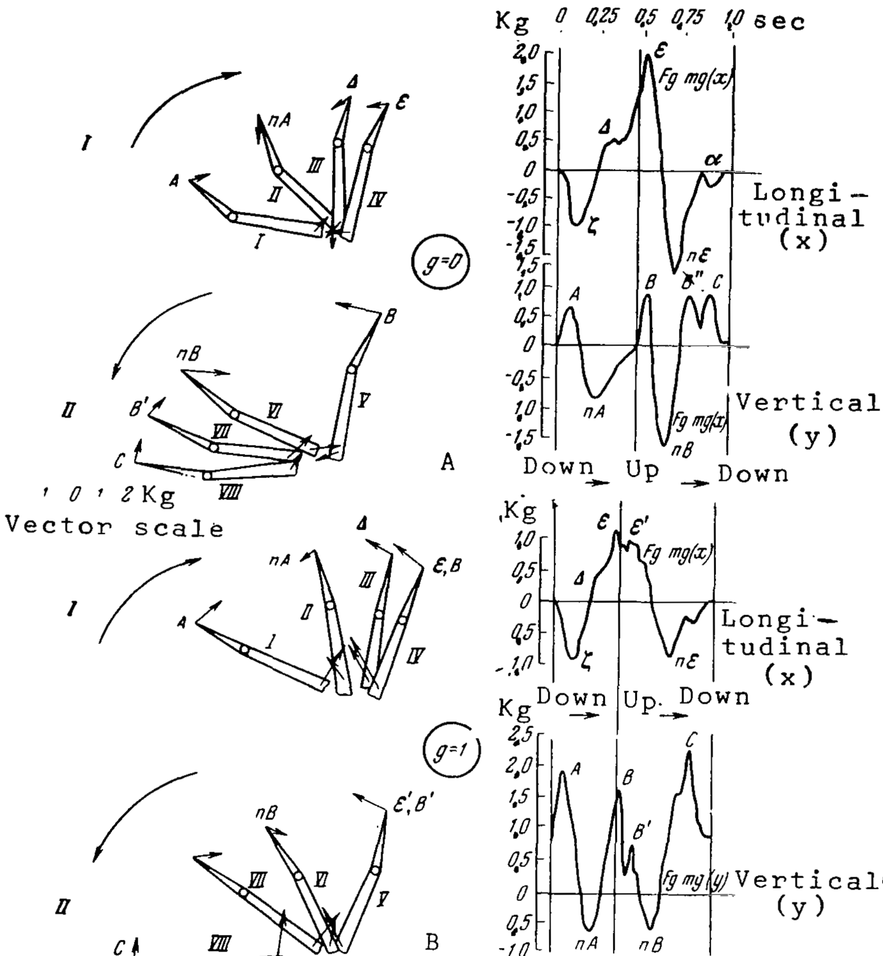
Fig. 26. Parametric curves of force components during the execution of flection and extension in a jerking motion. Orig.

Designation the same as in Figure 24.



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Change in components of forces (Fg) applied to gravity center of wrist (mg).

Fig. 27. Parametric curves of force components during the execution of target-aimed extension. Orig.

Designations the same as in Figure 24.

Following this, the longitudinal force component turns into zero /105
(the vertical remains, after a small peak of nA, at the same value) and forms there a small decelerating wave Δ. After this the summary force vectors abruptly change direction, to the reverse, and, although the flection has still not been completed, the sections of the arm begin to be decelerated (Fig. 24, Position III). However, there is nothing surprising in this. The forthcoming entire variation in the direction of the movement (transition from flection to extension) requires a preliminary halt of the forearm and wrist. Since it is necessary to cancel the inertia of the joints before this, the decelerating forces appear a long time before the completion of the flection. One proof of the validity of what we have said is that, in the execution of a flection by a burdened arm, this turn of the vector begins much earlier than in the movement of an unburdened arm (in Position II, and not in III, compare Figures 24 and 25).

What we have said illustrates very well the autonomy in the activity of the internal link controlling a skill (see Chap. I), which carries all this out without any interference of the higher divisions of the central nervous system, particularly of consciousness.

Following the complete deceleration of the arm sections, there is a smooth transition to extension, due to the previous deceleration. This is accompanied by the appearance of new spontaneous-innervation waves ε in the longitudinal components, and B in the vertical components of the forces. Both of these are very noticeable, and it is by them that the forearm and wrist are diverted foreward and downward. The question of their origin does not give rise to any doubts, since they are completely subject to the consciousness of the individual performing this skill. As a result of the combination of forces developed by these waves, the vectors applied to the centers of gravity of the wrist and forearm acquire the direction necessary for the beginning of the extension (Position IV of Figure 24 and 25).

The beginning of this movement is characterized by an abrupt decrease of both constituent forces, while a small break is always traced along the longitudinal component; this break is a satellite of the wave ε, and we have designation it as ε'.

The appearance of this is of a fundamental nature. To all appearances, it is a correction signal of the internal link controlling the performance of the skill. The latter can be proven to some extent in terms of the fact that it appears 0.12-0.14 seconds after the complete development of the principal wave. As was shown in Chapter I (Chkhaidze, 1962; Gurfinkel', 1965), the most important correction signals of this link, so important for the correct execution of a movement, enter at roughly the same rate.

After the movement is completely developed, the longitudinal force components again convert to zero (wave nε). It is by these again that the decelerating forces necessary for halting the arm in the completion of the movement are produced. As a result, the force vector again acquires the direction opposition to the course of the movement (Figures 24 and 25, Positions V, VI, and VII). During the execution of burdened extension, this vector not only is much greater in magnitude than in an execution by an unburdened arm , but it also acquires the requisite direction somewhat earlier (almost at the very beginning of the extension, Position V, Fig. 25). /106

Before the final halt of the arm, and consequently somewhat earlier than when the principal decelerating force C in the vertical components is developed, a concomitant reactive wave B shows through clearly on them; this is the second (extension being the first) reaction of the periphery to the movement of the wrist.

The execution of these movements by an unburdened arm in the form of a rapid jerking motion in 0.5-0.75 sec involves a certain rearrangement of the structure of the skill. In particular,the wave $\eta\gamma$ along the longitudinal components merges with the wave ζ, as is seen in the lower part of Figure 26 (right-hand side). The satellite of the wave A, or A^1, is absent here. The decelerating force Δ is very weakly pronounced. However, the opportune transition of the longitudinal components past zero permits the force vector to acquire the direction necessary for timely deceleration, as is seen in the left-hand part of Figure 26. Moreover, it develops much earlier than in the execution of a similar movement at a lower speed, which is in complete correspondence with the laws of mechanics (see Figure 24 and 26, Position III). Despite the high speed of the arm movement, the correction signal ε' nevertheless appears at the very beginning of the extension and during its execution in the jerking motion. At the same time, a certain general constraint in the motion leads to the situation where the curves are noticeably impoverished of breaks. In particular, there is no characteristic reactive wave B''.

The execution of an extension aimed toward a certain target was meant for studying how its movement structure changes when it is determined by a clear rational purpose.

Figure 27 (lower part) depicts the general picture of the accomplishment of this movement. The first part, or the preparatory flection, does not differ at all from the flection in the jerking motion described above, whereas the second extension, which also lasted no longer than 0.5 sec, was if interest in that very clear satellites ε' and B' were observed in the vertical force components. These were important correction signals. It is easy to see that the execution of an aimed extension required rapid and definite corrections, and they appeared in the form of these satellite-waves. It is possible that they had a spontaneous-innervation in this case.

Execution of the Indicated Movements Under Different Gravitational Conditions /107

If we turn to Figure 23, it is easy to ascertain that the structure of the skills cannot be identical under different gravitational conditions.

Even the external pictures of the trajectories for the movement of recognition points in the arm during the execution of such relatively simple skills as slow flection and extension are different.

If in the normal effect of the force of gravity the wrist and hand move is such a way that the trajectories for flection and extension actually coincide, then in weightlessness and at positive G-forces the ligting of an arm occurs along one course while a drop occurs along another one.

As a result of the effect of weightlessness, the external structure of the movements undergoes changes.

During the execution of slow flection and extension under weightlessness conditions (Figs. 24 and 25), there is a complete absence of B waves in the vertical force components and isolation of the reactive B'' waves and supplementary waves A' and $n\gamma$ in addition to a decrease in the values of the component forces (we will speak in more detail of this below).

The lack of a B wave can be explained by the fact that, under these conditions, the individual need not struggle with the force of gravity, and therefore all the forces of the extension can be directed only forward. This is very characteristic of the given case, and it indicates not only the correct rearrangement of the movement structure, but also the efficiency of the study methods we used. The very deep isolation of the satellite-wave ε' is a clear indication of the fact that, under the unusual conditions of weightlessness, the central nervous system of the individual should introduce additional corrections into the course of the skill performance through the internal control link. The same can also be said of the second flection waves A' and $n\gamma$. A substantial increase in the value of the reactive B'' wave indicates that there is a slight discoordination in the movement. The central nervous system could not cancel it out, which should always be the case in a sufficiently coordinated skill performance (Bershteyn, 1947; Chkhaidze, 1962).

This brings about a certain rearrangement of the vectors of forces applied to the centers of gravity of the wrist and forearm. They decrease and change direction from forward to decelerating with a noticeable lag (for example, in Position IV and not III, if compared to the upper and lower parts, Fig. 24), so that the lesser amount of inertia in the sections of the body simplify the deceleration process.

We can see definite differences in a comparitive evaluation of the values for the most important dynamic and kinematic characteristics of the components of slow flection and extension by an unburdened arm under the conditions of the normal effect of the Earth's gravitational field and in weightlessness (Table 8). /108

TABLE 8.

Differences in Order of Magnitude of the Most Important Components of the Structure of Slow Flection and Extension by an Unburdened Arm Under Different Gravitational Conditions (by the Gravity Center of the Hand).

Components	Normal Effect of Gravitational Fields	During Acceleration (2 g)	In Weightlessness
Dynamic characteristics at maximum, Kg			
Longitudinal			
Forces at the beginning of flection ($n\gamma$)	0.4	0.2	0.4
Decelerating forces at the end of flection (Δ)	0.3	0.2	0.2
Forces at the beginning of extension (ε)	0.9	0.3	0.6
Vertical			
Forces at the beginning of Flection (A)	1.3	2.4	0.3
Forces at the beginning of extension (B)	1.3	2.2	0.0
Reactive forces of extension (B'')	0.5	2.2	0.2
Decelerating forces at the end of the movement (C)	1.1	2.4	0.4
Kinematic characteristics at the extremum, m/sec			
Longitudinal velocity components	2.3	1.2	2.0
Vertical velocity components	2.1	1.0	1.6

Note the abrupt decrease in the values of the force vectors for weightlessress, which varies for different components. The vertical ones decrease almost by 75-80%, while the longitudinal ones decrease to 30-40%. This brings about a total 50%-decrease in the muscular forces expended. The greater decrease in the value of the vertical components compared to the longitudinal ones can be explained by the effect of the gravitational field on them. N.A. Bernshteyn (1935) showed that the vertical components of an individual's movements on the Earth reflect primarily the external mechanical aspect of this act - the struggle with the force of gravity, etc. This does not occur under weightlessness conditions, which is expressed in the greater decrease of the values of the vertical force components. This indicates that it is the longitudinal components, not the vertical ones, which play the leading role in the structure of the skill.

A slow flection and extension by a burdened arm executed under weightlessness conditions differs from the same accomplished by an unburdened arm, not only in the absolute values of the forces applied to sections of the arm (Fig. 25, upper part), but also in the fact that during its execution all the above-described breaks appear to be more "retouched". In particular, this concerns the even /109
clearer separation of the correction satellite-waves ε' and the increase in the value of the longitudinal components in the structure of the skill. The latter can be seen even in thefact that the most important spontaneous-innervation wave ε increases almost by a factor of 2. This is not surprising. The most complicated conditions for a movement (a burden five times heavier than the hand itself) required rearrangement of the skill structure precisely toward that side which was most effective under these conditions of weightlessness.

Summing up our comparitive analysis of slow movements under weightlessness conditions, we should consider it established that, during the execution of such skills by an individual in gravitational weightlessness, we can expect up to a 50%-decrease in the muscle forces, an increase in the role of the longitudinal force components (which should bring about a certain rearrangement of the movement structure), and a more frequent interference of the central nervous system into the course of the performance.

We considered the principal characteristic of the accomplishment of an aimed extension during the effect of a gravity force of one unit to be the appearance of the two satellite-waves ε and B in the curves for the force components at the beginning of extension.

Both of these satellites are absent under conditions of weightlessness (Fig. 27, upper part). Considering that this extension was executed during tha same time interval as for g = 1, we can assume that under conditions of weightlessness such a target-aimed type of rapid movement can be alleviated.

Finally, let us examine the execution of certain movements under conditions of the effect of positive G-forces from 1.8 to 2.2 g, which we studied as control observations.

Data on this experiment are given in Figure 28. The external conditions necessary for the execution of the skills were more complicated here. This led to a corresponding rearrangement of the movement structure. During the execution of slow movements, the parameters of the vectors of forces applied to the gravity centers of sections of the arm clearly increased, and the values of the vertical components increased by more than a factor of 2 (Table 8). The longitudinal components of the forces even decreased somewhat during this period. This confirms the above-presented concept, that in weightlessness the longitudinal components acquire the leading role in the structure of the movements. In correspondence with this, the reverse should occur during accelerations, which is observed in actuality. This is also reflected in a change of the direction of the summary force vectors. They are mainly directed upward, which permits the individual to fight successively against the increased gravity of the sections of the body.

It should be noted that the configurations of the curves (Fig. 28, upper part) are broken up to an extreme degree by very small waves.

Since this is linked with the introduction of correction-signals, we must assume that the unusual conditions under which the execution of this skill took place required a more freqent interference of the central nervous system into the course of this performance.

The execution of rapid movements under conditions of accelerations (for example, flection and target-aimed extension) occurs more intensely than at g = 1, and even more constrainedly than in weightlessness. The curves of the force components have very few breaks up to the end of flection (see Fig. 28, lower part). However, a very clear satellite of the wave ε' is noticed at the very beginning of such a complicated extension. It even exceeds the principal waves in size. If we consider that it does not exist in weightlessness (it is observed only at g = 1), we must assume that our concepts concerning the possible alleviation of control of an aimed movement in zero gravitational field are validified to a certain extent.

The summary vectors of forces applied to sections of the arm are noticeably increased during the execution of rapid movements in accelerations, compared to the execution of these movements at g = 1. Their greater inclination toward the horizontal than during the execution of slow movements is also normal, since abrupt jerks require a greater value of the longitudinal components. This changes the direction of the vectors, particularly those which characterize the forces applied to the gravity center of the wrist.

On the whole, we should mention that an analysis of the execution of these motions under conditions of accelerations not only confirmed the validity of many conclusions obtained during an investigation of their performance in weightlessness, but also showed the expediency of using our method. Thus, if we sum up

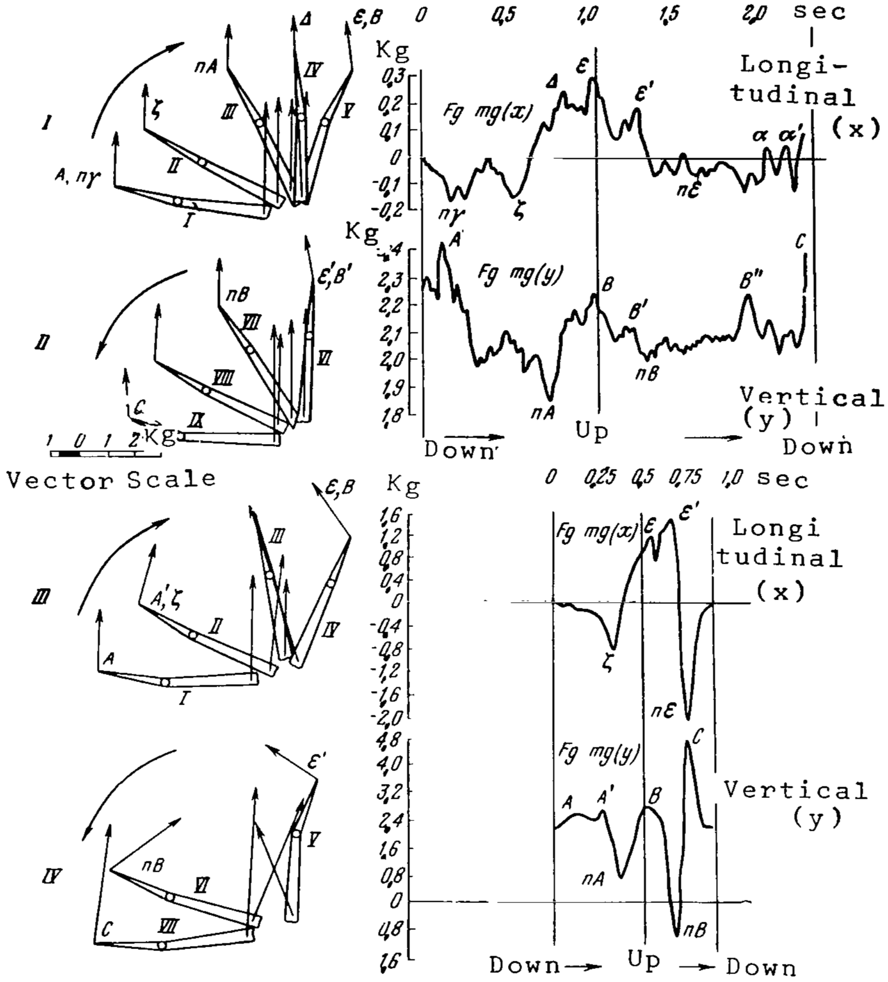

Fig. 28. Parametric curves of force components during the execution of slow flection (I), extension (II) and a similar movement in a jerk (III - jerk, IV - impact) under conditions of acceleration up to 2 g.

these observations, we can state the following: /111

1. Under conditions of temporary weightlessness, the value of the dynamic components of the coordination structure of movements decreases roughly by 1/2.

2. A certain rearrangement of it occurs simultaneously; this is expressed in the increased value of the longitudinal components and the small decrease in the value of the vertical ones.

3. Moreover, it is observed that the central apparatus regulating the development of the skill interferes more frequently with the coordination structure.

4. This appears somewhat less clearly during the execution of rapid movements than during the execution of slow ones.

This is all the more important since, as was shown in all the above-presented observations, a number of other investigations, and the self-observations of astronauts (see below), there are no more or less noticeable disorders in the coordination of an individual's movements in weightlessness on the whole. In the better case, we can observe a certain deterioration in the coordination at the beginning of a stay in weightlessness. /112

However, it seems to us that there are no contradictions here. The fact is that the preservation or restoration of the total movement coordination (i.e., differentiation of muscle forces, for pressures on a rigid support, and even handwriting) does not mean at all that the very fine internal structure of the skill, which appeared during its investigation only by such a scrupulous method as that of a cyclograph, remains unchanged. It is rather the opposite which can be anticipated. It is more correct to assume that the changed conditions of gravitation required precisely this rearrangement. Otherwise, there would be such exceedingly noticeable disorders in the coordination of the individual's movements that they would hit the researcher in the face. Therefore, we must consider as noteworthy, not so much the above-established facts, as just their existence, which ultimately allows an individual to maintain his movement coordination in weightlessness to such a degree that external impairments remain almost imperceptible.

Actually, if the value of the dynamic components does not change under conditions of weightlessness, while the central apparatus regulating the skill do not intensify their activity, and, finally, the role of the longitudinal components of the coordination structure does not increase, then the skill is not performed at all in the same way as in the normal effect of the Earth's gravitational field, with all the after-effects resulting from it.

A question arises here at the same time: Why is an individual's central nervous system so labile that it can rearrange its activity linked with the coordination of movements, even when there is disappearance of such a constantly-acting factor as the acceleration of the force of gravity, which had not changed during the course of millions of years?

Naturally, while there are no deep and exhaustive investigations connected with this phenomenon, we cannot give a detailed and experimentally-based explanation for this. However, we do consider it possible to say that, to all appearances, the change in accelerations of parts of the body in itself (which also means in the forces applied to them, since there is no difference between the force of gravity and that of acceleration) is not something unexpected for the central nervous system of man (and animals). The activity of this system takes place normally under those conditions when the moving parts of the body undergo accelerations which reach tens of g (for example, in strong ballistic movements). Even the above-studied flection and extension of an arm at the ulnar joint, which was executed rather abruptly, accelerates the movement of the wrist up to 7-8 g. It is true that such accelerations continue for about 1/10 of a second in all, but this has no significance in our case: if, after sufficient training, the central apparatus controlling our skills do not lose their ability /113 to coordinate movement correctly even at very high G-forces, and even when they are very brief, they are already capable of rapidly restoring these abilities, both during a prolonged effect of G-forces and during the disappearance of the effect of the Earth's gravitational field.

The stern school of evolution has somehow prepared them for this.

In 1967, I.F. Chekirda published some additional data on this question. Having reproduced these observations extensively (and having such people as V. Komarov and V. Bykovskiy as the testees), he investigated how the restoration of an individual's movement coordination takes place during the course of many brief periods of weightlessness. According to the data of I.F. Chekirda, such a restoration occurs in a definite phase sequence. In particular, there is first observed a certain complication of the structure accompanied by an increase in the dimensions and number of correction signals. I.F. Chekirda called this period the phase of surplus corrections (generalization). Then follows the phase of psuedo-reautomation, which reflects a gradual decrease in the role of the vertical force components, all the way to the establishment of a dynamic equilibrium with the longitudinal ones. The magnitude and number of correction signals decrease and approach the norm. Finally, in the third phase, or stabilization, there is a complete restoration of the movement coordination, accompanied by an abrupt decrease in the extrema and number of correction signals, a transfer of the leading role from the vertical components to the longitudinal ones, etc., i.e., all the phenomena characteristic of sufficiently automated skills. For the movement under investigation, this reflects the synclinization of its coordination structure (a decrease in the values of the summary forces, a decrease in the vertical components, etc.).

Naturally, all this takes place during the course of a certain amount of time, and not during one flight. Consequently, this process itself and its duration can serve as a convenient test of the development of an individual's training for a space flight, according to I. Chekirda. We can agree with this. However, the most important fact is that I.F. Chekirda's studies agree completely with our premises.

SUPPLEMENTARY DATA ON THE COORDINATION OF AN INDIVIDUAL'S VOLUNTARY MOVEMENTS UNDER CONDITIONS OF TEMPORARY WEIGHTLESSNESS

Finally, let us examine some other investigations of an individual's voluntary movements which are linked with their coordination under conditions of weightlessness, and which are interesting from general points of view.

The problem of the individual's ability to sustain steady /114 muscular force under conditions of short-term weightlessness (which is of particular importance for spacecraft control) has been studied by Ye.M. Yuganov et al. (1962). These observations, which also in many ways confirm our extrapolations, can be reduced to the testees' trying to sustain a given force (400 g) with his unsupported finger on the lever of a dynamograph throughout the stay in a zero field. This is also created during aircraft flights along a Kepler curve.

An analysis of the material amassed by this research has shown that if the testees maintained the prescribed force within fluctuation limits of ±10 g during horizontal flight (i.e., under the normal effect of the gravitational fields of the Earth), then in the first seconds of the weightlessness period, fluctuations in a 0-400 g range appeared. After many repetitions of this state, the capacity of the majority of the subjects to sustain the force at a certain level, which is close to the given one, was gradually restored.

Similar results were obtained earlier in approximately identical investigations by V.S. Gurfinkel', P.K. Isakov, V.B. Malkin et al. (1959), and by Ye.M. Yuganov, I.I. Kas'yan, N.N. Gurovskiy, V.I. Yazdovskiy et al. (1961).

In his study of the effect of weightlessness on the motor reactions of animals (the dogs Belka and Strelka) on board an artificial Earth satellite, B.A. Vhuravlev (1959) observed many similar phenomena reminiscent of restoration of motor skill coordination after initial disturbance.

The works of Gerathewohl (1957) and Weitside (1961) should be singled out for mention from foreign research concerning human voluntary motor impairments which are possible during temporary weightlessness.

These investigators conducted observations of the individual's ability to estimate the leading dynamic components of a skill during weightlessness, by retaining the ability to hit a target with a certain object, e.g., a special pen (Gerathewohl's experiments, 1957) or merely the finger (Weitside's experiments, 1961).

The observational results showed that when the individual's vision is blocked, he tends, as a rule, to miss the point at which the object is aimed. The researchers have called this the oculo-gravitational effect. It is in our opinion a completely valid indication of disturbances in the operation of the checking mechanism of the inner link, which controls the given skill, due to an abrupt disturbance of the control information. A simple demonstration of this is the fact that Gerathewohl and Weitside are /115 in agreement regarding the gradual restoration of the described skill (i.e., decrease in the oculo-gravitational effect) during the individual's repeated and multiple sojourns under conditions of weightlessness.[4] This agrees with the above-quoted data of Soviet scientists, and indicates precisely the reasons for the disturbances therein in zero gravitational fields, and the origin thereof, since - as we have repeatedly explained - the capacity for monotonic regeneration of the movement structure parameters is only inherent to the inner link, which regulates this movement.

To sum up the research on possible changes in the coordination of an individual's voluntary movements under conditions of short-term weightlessness, we must point out that all statements have led to basically the same conclusions: the initial deterioration of the skill pattern, which is caused by an abrupt change in the control information, must - as the adaptation of the individual in the zero gravitational field advances - be replaced by the restored parameter values of this pattern, and in the final analysis must lead to normal, or close to normal, movement coordination.

From all evidences, this restoration should not require much time. This conclusion has been corroborated in artificial manned satellite flights around the Earth.

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[4] Gerathewohl, for example, clearly states the following: "The testees adapted themselves to weightlessness in the first six experiments (italics ours - L. Chkh). This is evident from the fact that the target is hit more accurately when the force of gravity decreases than when it increases." (J. aviat. Med., Vol. 28, No. 1, pp. 7-12, 1957.)

VOLUNTARY MOTOR COORDINATION OF MAN UNDER CONDITIONS OF PROLONGED WEIGHTLESSNESS

The literature at present lacks data on sufficiently extensive investigations of human voluntary movement coordination in prolonged weightlessness, e.g., data similar to those cited above. This deprives us of the opportunity of clarifying this matter in sufficient detail, but we can expect justified considerations about it by taking into account a number of observations (and self-observations) of Soviet and American astronauts.

All the Soviet and American astronauts agree in stating that they experienced no movement coordination disturbances under orbital flight conditions.

We can form a rather detailed opinion of this derived from data from G. Titov's report on his sensations during flight, which are quoted in the collection The First Space Flights by Man (1962).

"At the beginning of the flight (2 hours after lift-off), when performing vestibular tests, whose order of performance had previously been indicated in the log in the form of little drawings, /116
the astronaut observed no difficulties or errors. He executed the movement coordination test with closed eyes easily and accurately."

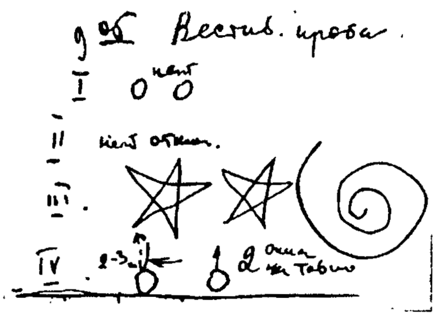

Fig. 29. Vestibular tests and handwriting of G. Titov on Earth (while in the mock-up of the "Vostok" spacecraft).

"With closed eyes he easily and correctly drew five-pointed stars and two-and-one-half-turns spiral, as he had under terrestrial conditions. On his own initiative, he touched the control levers and other objects an arm's length away several times in succession, without any mistakes and with eyes closed. Movement coordination, according to G. Titov's statements was not impaired through the flight."

Figures 29 and 30 reproduce samples of G. Titov's handwriting and the drawings mentioned in the above collection, which were made under terrestrial conditions (in the mock-up of the spacecraft) and in space flight. It can be

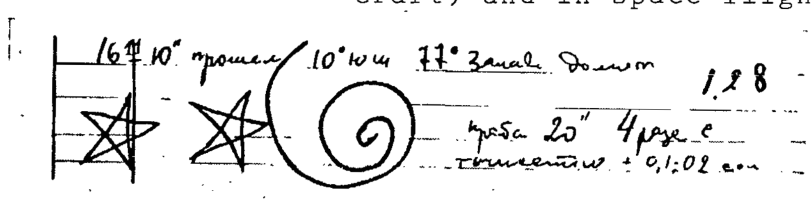

Fig. 30. Vestibular tests and handwriting of G. Titov in space flight.

readily seen that no perceptible disturbances in writing or in manner of executing the designs can be traced.

From the personal impressions of astronauts, it is fitting to quote an excerpt from the report of John Glenn to NASA in the USA.

He writes: "In a sitting position at zero gravity, I felt more comfortable than in the same position on Earth at 1 g, since I experienced no pressure. I very quickly adapted to the state of weightlessness (italics our - L. Chkh.). I had no intention of taking any premature measures. I experienced no signs of coordination impairment (of movement - L. Chkh.), even in the first moments after separation (of capsule from carrier rocket - L. Chkh.). I unconsciously took advantage of the state of weightlessness, /117
paying no attention, for example, to the objects floating in the capsule - cameras (moving picture - L. Chkh.), etc. I was otherwise occupied. This behavior had not been thought out in advance, but was dictated by the situation itself, since another system (he is speaking of controlling the capsule - L. Chkh.) required my attention. The thought later occurred to me that my behavior then was just as natural as though the movie camera were lying on a table under 1 g conditions. I have been able to give only a poor illustration of how fast the human body adapts to conditions which are as foreign to it as weightlessness."

These observations continued during the following orbital flights.

As indicated in a report by V.I. Yazdovskiy, I.I. Bryanov, L.I. Kakurin, Yu. I. Krylov and M.A. Cherepakhin at the Conference on Aviational Space Medicine held in 1963, the cosmonauts A.G. Nikalayev and P.R. Popvich successfully carried out the following tests in flight: with closed eyes, directing their hands to an object and evaluating their position within 20 seconds; with open and closed eyes, drawing a three-looped spiral, a five-pointed star, and two horizontal and two vertical parallel lines.

The first test was carried out in an identical manner on the ground and in flight. The second was usually carried out in a better manner with the right hand than with the left hand in weightlessness, but in an identical manner with both hands during accelerations.

From this the authors concluded that "... the state of weightlessness does not lower the quality of the sensory-motor coordination in its concrete form, which state takes place during the execution of review tests ...", and further, "... the quality of the cosmonauts' performance was not lower, but even higher, than on the Earth ..."

This coincides with the personal impressions of these astronauts.

P.R. Popovich emphasized that "all the tests in weightlessness had even better results than on the Earth. I drew very well. My hand was very steady, the pen wrote out straight lines, even with my left hand, while my right one did very well as usually ...", and further, "... I worked with all the electrical switches with closed eyes. I tried to work in darkness, as when you enter the shadow (of the Earth, L. Chkh.), or you shut off the lights and the craft is in complete darkness. Even then your hand goes where you want it. I was lying down, but I knew that the switches were there and the radio was right there. I held out my hand and turned on the light."

A.G. Nikolayev stated that "the equipment can be handled completely in weightlessness. The records and sketches made in weightlessness do not differ at all from those made under terrestrial conditions. All movements are coordinated."

Naturally, it would be difficult to think up more surprising facts indicating the maintenance, or at least rapid restoration, of an individual's movement coordination under conditions of weightlessness, but the authors of this report emphasize in particular that all the facts were recorded, not during the very first moments of the stay in weightlessness, but somewhat later. Therefore, the restoration restoration period must in some way be examined in more detail, so much the more so since, for example, P.R. Popovich mentioned that "the novelty of the sensations causes tension in the execution of the performance". /118

We can agree with this totally if we consider the data of the studies we carried out. However, this period can be very short.

In a personal discussion with the authors of these lines, the astronaut B.B. Yegorov said that neither he nor his fellow travellers sensed any disorders in their movement coordination. "Moreover," Yegorov said, "Komarov and I threw each other our food-wrapping several times in order to test our sensations, but both the throwing it and catching it were accompanied by completely coordinated movements".

When asked whether or not he followed up the period of movement coordination restoration, B.B. Yegorov answered that he did not notice it.

It must be assumed that this period was apparently very short and that the lift-off tensions concealed it from the astronaut.

MOVEMENT COORDINATION OUTSIDE THE SPACECRAFT

The coordination of an individual's voluntary movements outside a spacecraft has been studied very little to the present, but investigations in this direction were begun the first time man went into outer space. In particular, Ye. Evenov, V. Popov and L. Khachaturyants, in an article entitled "Orientation and Activity of Man in Reference-less Space", in the journal Avitsiya i Kosmonavtika, No. 7 for 1966 (pp. 20-24), amassed a detailed but general biomechanical picture of the movements of A.Leonov, which had been photographed on a movie film during his stay outside of the spacecraft.

Although it is easily seen that the general effect of weightlessness on an individual remains unchanged both in a craft and outside of it, two factors come into play in open space - the presence of a G-suit on the astronaut, which changes the mobility of his joints or extremities to some or another degree, and the absence of a reference, which is so necessary for man in order that he may perform any locomotions. Both of these factors, together with weightlessness, left a certain imprint on Leonov's movement under investigation.

Nevertheless, as the authors have shown, even the first conclusions from the materials obtained showed that ... "the characteristics of the movements during the entries out of the craft into open space differed very little from the same characteristics /119
during training on an aircraft"...

Somewhat greater differences were obtained in an analysis of the velocity characteristics. As the authors showed, the differences here reached 20-30%, and even 50% at the maxima.

Having evaluated the degree to which the motor skills developed on the Earth were preserved during an entry into outer space by comparing the maximum velocities and accelerations, as well as the physical forces developed in this respect, to those which took place in similar situations during temporary weightlessness in aircraft training, the authors (using a special coefficient) drew the conclusion that ..."the quality with which A. Leonov performed his exercises in outer space was lower than the quality with which he performed the exercises in a laboratory-aircraft during a flight along a Kepler trajectory (K = 57-60%), but much higher than during his first training (K = 27-28%)". From this the authors made the important conclusion that ..."training in flight and in static tests imitating reference-less space showed a substantial effect on the development of the skills controlling orientation and movement of a body in open space"...

On the whole, the studies of Ye. Ivanov, V. Popov and L. Khachaturyants showed that our concepts concerning the basic possibilities of maintaining (for corresponding preparation) the coordination of an individual's voluntary movements in weightlessness also can be expanded in the most part to his reference-less position in open space.

The authors showed directly that ..."the skills and movement coordination developed during terrestrial and aircraft training were preserved during the astronaut's entry into outer space, and the astronaut was capable of performing purposeful coordinated movements and relatively simple working operations"...

In summarizing what has been said, we must therefore note that even prolonged weightlessness causes no changes in the individual's movement coordination, which could result in a marked decrease in his ability to work, but to assert that he always maintains it under any circumstances would also be incorrect. From all appearances, we must assume that adequate and proper training should guarantee its restoration after a specific disturbance of a certain duration. However, the problem of the subsequent state of movement coordination during a very prolonged stay (weeks or months) by a human being under conditions of weightlessness is still naturally unclear.[5]

There is still a basis for assuming, however, that from all the findings the far greater danger in this regard lies in an individual's prolonged stay in increased gravitational fields. Here the weight increase of the extremities and the resultant drastic distortion of control information can lead to a more profound and extended impairment of the movement coordination for a person in such a field. /120

CONCLUSIONS

The data cited in this chapter make it possible to draw the following conclusions:

1. An individual's stay in a zero gravitational field should involve no serious disorders of voluntary movement coordination if he has been adequately trained for the stay. A possible initial deterioration of the quality of the motor skills to be executed, which is caused by the transition to unusual conditions, is relatively rapidly replaced by the stable performance of the requisite dynamic components of the movement coordination pattern.

2. Proper training directed toward a goal may, however, minimize these disorders, and bring about the gradual restoration of movement coordination, even in increased (within a certain limit) gravitational fields.

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[5] According to recently published data (see A.A. Leonov, V.I. Lebedev, Perception of Space and Time in Outer Space, Moscow, "Nauka", 1968, pp. 57-64), our concepts coincide completely with the actual state of affairs - the rough coordination of movements is practically undisturbed if the astronaut is sufficiently prepared, while the fine coordination is restored during the course of the first few days of flight.

3. In the execution of movements in the altered effect of a gravitational field, certain changes should also be expected in the dimensionality of the dynamic components of the coordination structure of the skills (including the leading components - direct muscular forces). In this regard the limits to the decrease of the elements of the movement structure can reach 50% in weightlessness.

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"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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